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Engineering Note

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Project: Solenoid Energization, Controls, Interlocks and Quench Protection
Doc. No: H960814A

Subject: Solenoid Dump Resistor - By W. Jaskierny

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D Zero Dump Resistor

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Design Requirements:

1. This resistor is to be used as a parallel dump resistor, that is in parallel with the load inductance.
2. 4825 Amp current in the solenoid circuit.
3. Solenoid inductance of 0.48 Henrys.
4. Bus resistance, there are two possible locations to install the dump resistor at. The "T" between the assembly and collision hall, bus resistance at this point should be 0.666 mOhms or approx. 3.5 Volts steady state bus voltage. The second location is near the power supply room with a bus resistance of 1.332 mOhms or approx. 7.0 Volts steady state bus voltage.
5. The maximum output voltage of the power supply during the solenoid charging is approx. 15 volts DC. Near the end of the charging cycle of the solenoid, the voltage at the "T" location is approx. 11.7 Volts DC. The voltage at the power supply location room is approx. 15 Volts DC.
6. Charging time of the solenoid with a 15 Volt power supply tap is approx. 40 minutes.
7. 250 Volts developed across the dump resistor during a dump.
8. 5.6 MegaJoules absorbed by the dump resistor during a dump.
9. 60 degrees C temperature rise of the dump resistor.
10. 40 degrees C maximum ambient temperature.
11. The dump resistor is to be convection cooled.

Flat stock 304 stainless steel is to be used for the dump resistor because of availability,high density, and high resistance per unit of length.

304 SS has the following listed properties:

specific heat = approx. 460 Joules/degree C kg [1.]

specific weight = 0.00784 kg/cm^3 or 0.283 lb/$in.^3$

specific resistance at 20 degrees C = 72 µOhm-cm or 28.35 µOhm-in.

resistance temperature coefficient per degree C = 9.4×10^{-4}

resistance at 100 degrees C = 1.0752 $R_{20 \text{ degrees C}}$

For 1/4" x 4" 304 SS bar stock the following can be determined:

resistance at 20 degrees C = 0.3401 mOhm/ft.

weight = 3.4 pounds per foot

Mechanical layout of resistor:

Using 1/4" x 4" 304 SS bar stock for the resistor then for 50 mOhms at 20 degrees C the length is 147 feet. For 12 each 12 foot sections the length is 144 feet giving a resistance of 48.97 mOhms. It is recommended that the dump resistor be constructed using 12-12 foot lengths of bar stock parallel to each other connected on the ends for a zigzag pattern, with the 4 inch surface of the bar stock in the vertical plane. The vertical surface area of this part of the resistor is 13824 $in.^2$. To maintain laminar air flow through the resistor a spacing of 1.5 inches is recommended between the bars. The end jumpers for the resistor will be 11 pieces of 1/2" x 4" x 1 1/2" 304 SS resulting in an additional 0.23 mOhms of resistance and vertical surface area of 132 $in.^2$.

The total weight of this resistor is 498.95 pounds or 226.8 kg.

The total resistance is 49.2 mOhms at 20 degrees C.

The total vertical surface area is 13956 $in.^2$

DC steady state heating effects:

The free convection heat transfer coefficient can be determined by the following formula: [2.]

$h_c = 2.21(10^{-3})(\text{delta } T/L)^{.25}$ watts/$in.^2$ degree C

delta T = the temperature difference between the surface and the ambient air

L = vertical length of the surface in inches

The radiation coefficient can be closely approximated be the following equation: [2.]

$h_r = 1.47(10^{-10})(e)(1-F)(\text{delta } T/2 + 273)^3$ watts/in.^{2} degree C

e = surface emissivity (use 0.55 for 304 SS)

F = shielding factor due to stacking (use 0.665 for 4" plates 1.5" apart)

delta T = the temperature difference between the surface and the ambient temperature

The power dissipation of the resistor from convection and radiation cooling can be determined by the following formula: [2.]

$q = (h_c + h_r)(A)(\text{delta } T)$

A = Vertical area in square inches

delta T = the temperature difference between the surface and the ambient air

For a dump resistor located at the "T" during the steady state condition of a charged solenoid:

If a 6 degree C temperature difference is assumed from the DC heating effect then

$h_c = 2.446(10^{-3})$ watts/in.^{2} degree C

$h_r = 0.569(10^{-3})$ watts/in.^{2} degree C

For an area of 13956 in.^{2} and a delta T of 6 degrees C then q =252 watts.

The actual DC power dissipation of the resistor at 46 degrees C, due to effect of increasing resistance with a increase in temperature is 243 watts which is in close agreement with the previous calculation.

For a dump resistor at the second location near the power supply during the steady state condition of a charged solenoid:

If a 18 degree C temperature difference is assumed from the DC heating effect then

$h_c = 3.219(10^{-3})$ watts/in.^{2} degree C

$h_r = 0.607(10^{-3})$ watts/in.^{2} degree C

For an area of 13956 $in.^2$ and a delta T of 18 degrees C then q = 961 watts.

The actual DC power dissipation of the resistor at 58 degrees C, due to effect of increasing resistance with a increase in temperature is 961 watts which is in agreement with the previous calculation.

Temperature rise from fast dump:

The temperature rise of the dump resistor during a fast dump can be determined by the following formula. [3.]

delta T= (1/2 L I^2) / M C

M in kilograms

L = inductance of solenoid

I = current in solenoid

C = specific heat resistor material in Joules / degree C kg

delta T = temperature rise in degrees C

The temperature rise due to a fast dump of the resistor will be 54 degrees C.

Therefore with a ambient air temperature of 40 degrees C the maximum temperature of the dump resistor will reach is 100 degrees C at the "T" location or 112 degrees at the power supply location for a fast dump during steady state operating conditions. This is assuming standard atmospheric pressure, and no nearby structures inferring with the radiation of the resistor.

Worst case conditions:

If the temperature rise of the dump resistor is calculated for a scenario of a fast dump at the end of the charging cycle of the solenoid (maximum DC heating), the following is the result.

For a dump resistor located at the "T" during charging:

If a 41 degree C temperature difference is assumed from the DC heating effect then

$h_c = 3.95(10^{-3})$ watts/$in.^2$ degree C

$h_r = 0.685(10^{-3})$ watts/$in.^2$ degree C

For an area of 13956 $in.^2$ and a delta T of 41 degrees C then q =2652 watts.

The actual DC power dissipation of the resistor at 81 degrees C, due to effect of increasing resistance with a increase in temperature is 2632 watts which is in close agreement with the previous calculation.

For a dump resistor at the second location near the power supply during charging:

If a 60 degree C temperature difference is assumed from the DC heating effect then

$h_c = 4.35(10^{-3})$ watts/in.^{2} degree C

$h_r = 0.753(10^{-3})$ watts/in.^{2} degree C

For an area of 13956 in.^{2} and a delta T of 60 degrees C then q = 4273 watts.

The actual DC power dissipation of the resistor at 100 degrees C, due to effect of increasing resistance with a increase in temperature is 4253 watts which is in close agreement with the previous calculation.

If the previous calculated temperature rise of the dump resistor during a fast dump of 54 degrees C is used with a ambient air temperature of 40 degrees C and the additional temperature rise of the charging voltage conditions, the maximum temperature of the dump resistor will reach is 135 degrees C at the "T" location or 154 degrees at the power supply location.

These temperatures are higher than what was outlined in the design requirements. But this is for worst case conditions of a high ambient air temperature and a quench at the end of the charging cycle of the solenoid. A quench is more likely to occur when the rate of rise of the current through the solenoid is the greatest during the earlier part of the charging cycle and as a result there would be less energy stored in the solenoid. Forced air cooling could be used during solenoid charging and after a fast dump to reduce the resistor temperature. The insulating spacers for the stainless steel bar stock is to be made out of Teflon (TFE) which has a maximum working temperature of 250 degrees C [4.]. This insulating material should not have any problems at a possible maximum temperature of 155 degrees C..

References:

1. Heat Transfer, J.P. Holman, 1981

2. GE SCR Manual, Third Edition, 1964

3. FNAL TM-1611, A.T. Visser, March 1990

4. National Electric Code, 1993 edition